Immersion lithography; its potential performance and issues

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ABSTRACT

Imaging performance and issues of immersion lithography are discussed with the results of the recent feasibility studies. Immersion lithography has advantage in the numerical aperture of optics by a factor of refractive index n of the liquid filled into the space between the bottom lens and wafer. In case of 193nm exposure, water (n = 1.44) has been found as the best liquid. It is shown, by using imaging simulations, that ArF (193nm) immersion lithography (NA=1.05 to 1.23) has equivalent performance to F2 (157nm) dry (NA=0.85 to 0.93) lithography. Six fundamental issues in the ArF immersion lithography are investigated and studied. Results of the study indicate that there are no "show stoppers" that prevent going into the next phase of feasibility study.

Keywords: Immersion lithography, exposure tool, imaging simulation, 193nm extension, wavelength change

1. INTRODUCTION

Immersion lithography[1,2] has been considered as an effective method that improves the resolution limit of the given exposure wavelength. However, it has not been seriously considered as an actual method partly because of the difficulty in full-field projection optics design and partly because of difficulties in actual implementation of liquid-handling system in exposure tools.

On the other hand, it is gradually understood that the wavelength change takes time more than expected, especially in the case of change from KrF (248nm) to ArF (193nm). In addition, estimated high costs of new wavelength exposure tools are becoming concerns. Based on these facts, ArF immersion lithography has generated much interest as a new candidate for 65nm lithography[2], as well as F2 immersion for 45nm lithography[1].

In this paper, we first investigate the expected performance of immersion lithography by optical imaging simulations. In those simulations, we adopt full-vector treatment of electromagnetic field. That means all polarization effects are considered within. Capability of ArF immersion is compared with F2 dry system.

Next we list and discuss the issues of immersion lithography. They are:

1) Existence of full field projection optics and limit of NA

2) Precise measurement of water parameters, especially, $n(\lambda)$, dn/dT

3) Thermal aberration by the water temperature change, especially heat with exposure laser pulses

4) Water supply and recovery system

5) Bubble prevention and elimination

6) Resist availability for 193nm water-immersion

On these items, we report the latest results of the study made inside Nikon, and results of collaborative work with TOK on the imaging experiment for immersion resists. In the last part, we describe the schedule of the Nikon feasibility study in addition to discussion on wavelength change strategy.

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2. POTENTIAL PERFORMANCE OF IMMERSION LITHOGRAPHY

Immersion lithography uses some kind of liquid filled into the space between the bottom lens and wafer (Figure 1).

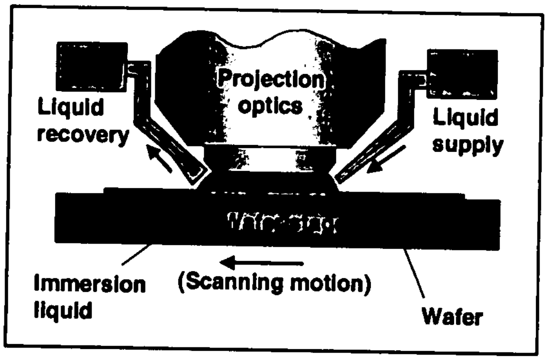

Figure 1 Exposure tool for immersion lithography

The numerical aperture (NA) of projection optics is defined by:

$$NA = n \sin \theta .$$

Where n is the refractive index of the medium (liquid, gas or vacuum) of the focal region, θ is the maximum incidence angle. Because the n is generally larger in liquid (typically 1.3 - 1.4) than the air or gas, NA can be higher than that of conventional system (dry system) with the same incidence angle θ.

Generally speaking, the resolution limit of the optical exposure system is given by a formula;

$$R = k_1 \frac{\lambda}{NA} = k_1 \frac{\lambda}{n \sin \theta} = k_1 \frac{\lambda / n}{\sin \theta} .$$

Where k_1 is a constant. We have the advantage of factor n in the resolution. On the other hand, we can understand the wavelength λ is reduced to an effective wavelength λ/n. Considering the λ/n, we can compare the potential advantage of immersion lithography with conventional wavelength lithographies (Table 1).

	medium	n	λ/n	ratio
ArF dry	Air	1.0	193nm	1.00
F2 dry	N_2	1.0	157nm	0.81
ArF immersion	H_2O	1.44	134nm	0.69
F2 immersion	PFPE	1.37	115nm	0.60

Table 1 Comparison of effective wavelength (λ/n) for dry and immersion lithography.

Exact resolution analysis requires careful treatment; in other words, there are several k_1 factors for several different masks and process conditions. For more precise understanding, we have to simulate the depth of focus (DOF) by using ED-tree method. We also have to use a full vector treatment model of optical imaging.

2.1 Immersion lithography performance: Line and space pattern with binary masks

Figure 2 shows the results of imaging simulation on the line and space (L/S) patterns with binary masks.

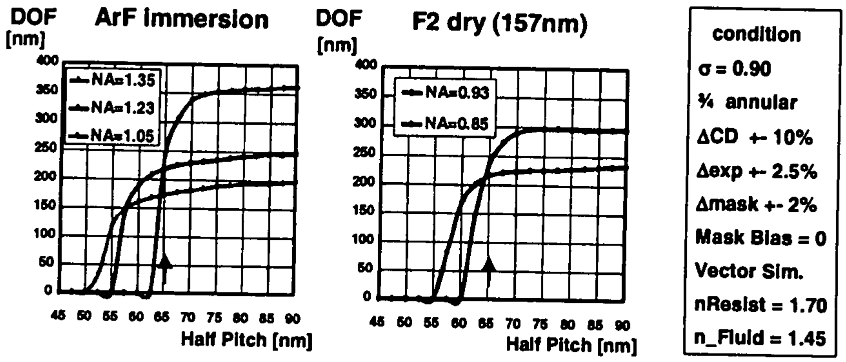

Figure 2 DOF vs. half pitch for L/S with binary masks. Vector electric field treatment and ED-tree method are adopted. Random polarization condition is assumed.

In this simulation, we treated the electromagnetic wave as a vector field, so that all polarization effects are considered. We assumed a random polarization here. As we can see from figure 2, ArF immersion of NA=1.05 has the capability of 65nm L/S, which is equivalent to that of F2 dry NA=0.85. In addition, 60nm L/S becomes possible by ArF immersion NA=1.23, as well as F2 dry of NA=0.93 with binary masks.

2.2 Immersion lithography performance: Isolated hole with attenuated PSM

Figure 3 shows the results of imaging simulation on isolated holes with attenuated phase shift masks.

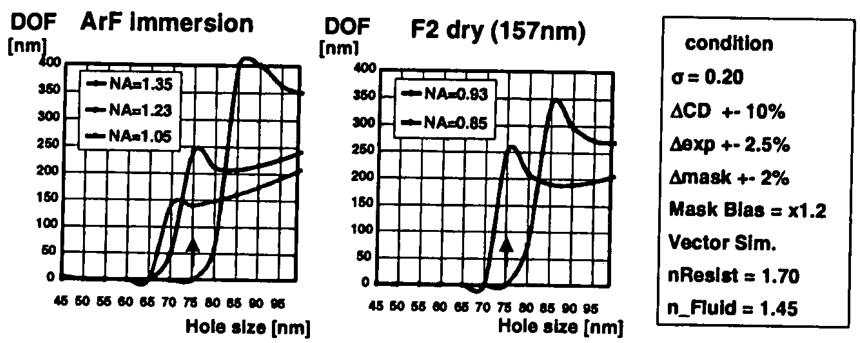

Figure 3 DOF vs. hole size with attenuated phase shift masks. Vector electric field treatment and ED-tree method are adopted. Random polarization condition is assumed.

In the previous simulation, full vector treatment and random polarization are adopted. It is shown that 75nm isolated holes are possible in both cases of F2 dry NA=0.93 and ArF immersion NA=1.23. 85nm holes are possible by both F2 dry NA=0.85 and ArF immersion NA=1.05.

2.3 Immersion lithography performance: L/S pattern with alternating PSM

Figure 4 shows the results of imaging simulation on the L/S patterns with alternating phase shift masks and F2 immersion. Line and space patterns of 45nm half pitch (line width) are expected by F2 immersion NA=1.23, with a DOF of nearly 200 nm. This can be understood as the case of ultimate optical lithography.

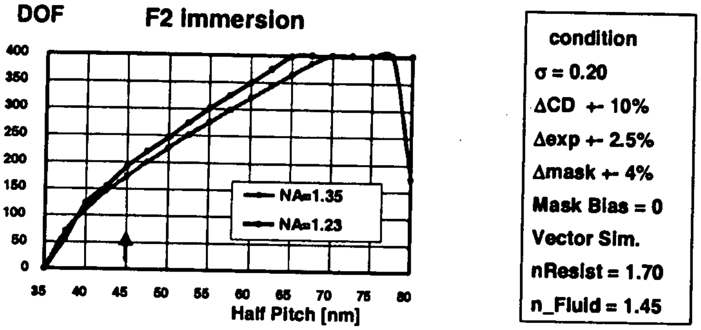

Figure 4 DOF vs. half pitch of L/S patterns with alternating PSM and F2 immersion. Vector electric field treatment and ED-tree method are adopted. Random polarization condition is assumed.

2.4 Immersion lithography performance summary

To summarize the advantage of immersion lithography, we can understand that ArF immersion of NA=1.05 has almost equivalent performance with F2 dry NA=0.85. In both cases, it is possible to image 65nm L/S with binary masks (and 55nm L/S with alternating PSM, although not described above). ArF immersion of NA=1.2 has almost equivalent performance with F2 dry NA=0.9. Both cases have capabilities of 60nm L/S with binary masks (and 50nm L/S with alternating PSM). F2 immersion has potential to reach the 45nm node by using alternating PSM.

3. ISSUES AND FEASIBILITY STUDY RESULTS

Six fundamental issues are investigated. They are 1) Existence of full field projection optics and limit of NA, 2) Precise measurement of water parameters, especially, n(λ), dn/dT, 3) Thermal aberration by the water temperature change, especially heat with exposure laser pulses, 4) Water supply and recovery system, 5) Bubble prevention and elimination, 6) Resist availability for 193nm water-immersion.

3.1 Full field projection optics.

Nikon has undertaken design of full field (26mm width) projection optics. In case of NA=1.05, we have obtained a design whose aberration correction is good and the total size of optics fits the conventional platform of exposure tools. For the NA=1.20, a design of good aberration correction was obtained; however, the total size is bigger than the size acceptable by conventional platforms. We are trying to improve the total size, and we think there is a chance. In the case of NA=1.30, we have not yet obtained any design with good aberration correction, even if very big size is assumed.

3.2 Precise measurement of water parameter

International SEMATECH (ISMT) has formed a taskforce on immersion fluid properties and is working with NIST on the measurement of these properties. It is generally believed that NIST will be successful in the precise measurement of refractive index and its temperature coefficient, dn/dT. Temperature coefficient dn/dT is initially estimated as $-2.0 \times 10^{-4}\ K^{-1}$.

3.3 Thermal aberration by exposure light

Exposure light heats up the resist, BARC, wafer and the water. If the water is heated inhomogeneously, it will cause optical aberration (thermal aberration). Because the temperature coefficient $dn/dT = -2.0 \times 10^{-4}\ K^{-1}$ of water is very large compared with that of gas (typical value of air, $dn/dT = -0.9 \times 10^{-6}\ K^{-1}$), we should be careful about this effect. We have conducted thermal simulation using typical parameters of ArF exposure condition. Pulse energy density of $0.2 mJ/cm^2$ and pulse duration of 50ns (uniform intensity) are assumed. The water directly absorbs some part of exposure energy, but it is less than 3% for 1mm thickness water, according to the latest measurement of water absorbance. Most of the exposure light energy is absorbed by the resist and BARC. Using typical thermal

parameters of silicon wafer, BARC, resist and water, we calculated the temporal change of water temperature. Figure 5 shows the result:

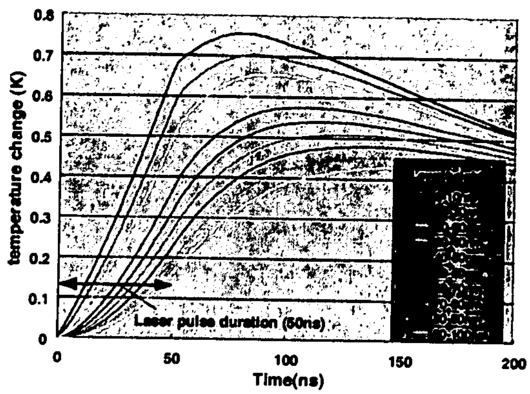

Figure 5 Temperature change of water heated by an exposure light pulse.

In figure 5, temperature changes of multiple layers are shown. The layer nearest to the resist interface (0-10nm layer) has the temperature increase by 0.7K, and the layer of 90-100 nm has temperature increase of 0.15K at the end of exposure light (50-ns pulse). After the pulse, temperature of every layer goes to a maximum value, but it does not affect the aberration of the exposure. By another time-extended simulation, we know the temperature change of every layer returns to negligibly a small value before the next pulse exposure.

We can estimate the magnitude of thermal aberration. Effective thickness of the heated layer can be regarded as less than 200nm (based on the fact that the temperature increase at 90-100 nm is less than 1/4 of 0-10 nm change). Next, the temperature increase of this effective thickness layer is 0.7K as the worst case. Combining the measured parameter of $dn/dT = -2.0 \times 10^{-4}\ K^{-1}$, we can understand the worst case of wavefront aberration is;

$$200\text{nm}\times 0.7\text{K}\times\left|-2.0\times 10^{-4}\text{K}^{-1}\right| \approx 0.03\text{nm} \approx 2\times 10^{-4}\times(193\text{nm}/1.44) = 0.2\text{m}\lambda\ ,$$

where wavelength λ is now the effective wavelength of the exposure light in the water, which is 193nm divided by the refractive index 1.44. Considering the recent requirement on the wavefront aberration for the imaging optics, which is the order of several mλ, we can conclude the thermal aberration cause by the exposure pulse is negligibly small.

We should note that this is limited to the exposure light pulse heating case. We should be very careful about the temperature control of the water, because the total optical path in the water will be the order of 1mm, which is 5000 times thicker than 200 nm evaluated in the above estimation.

3.4 Water supply and recovery mechanism

There are three categories of methods proposed for the liquid supply and recovery. Figure 6 shows these methods.

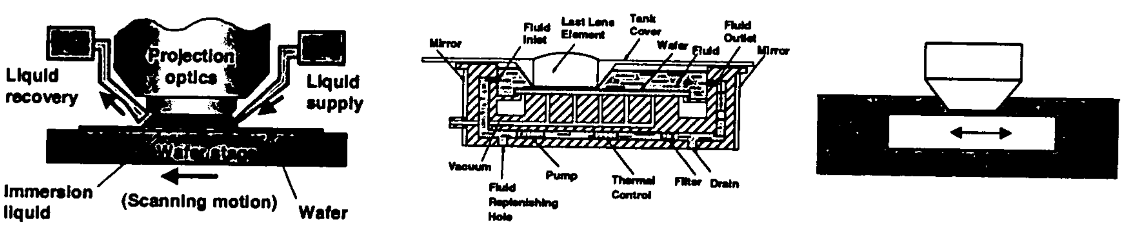

Figure 6 Liquid supply and recovery methods. Local fill (left), wafer immersion (center)[2], stage immersion (right).

Local fill method (left) has the advantage that the change from the conventional (dry) system is minimum. However, it brings about difficulties for "edge shots", which means difficulty in keeping the water layer when shots near the wafer edge are exposed. Wafer immersion method[2] (center) does not have the difficulty of "edge shot", however, the quick motion of the wafer stage will be prevented by unstable motion of the water contained inside the stage. Stage immersion method needs big container of water; it will be almost lower half of exposure tool. It is not considered as a feasible idea.

Nikon has concentrated on the feasibility study of the local fill method. Many cases of fluid dynamic simulation were made. In figure 7, the first case of simulation result is shown.

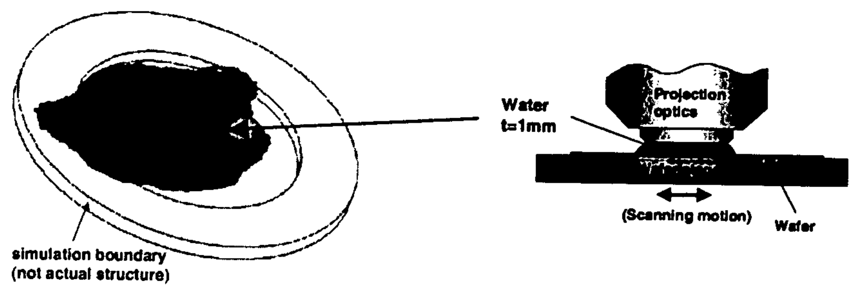

Figure 7 Fluid dynamic simulation result for local fill method; no supply, no recovery case.

In this simulation, the initial condition is set so that the water exists between the bottom lens and wafer, and it is stationary due to the effect of the surface tension. Typical physical parameters are assumed about the water and surface conditions. After the initial condition is satisfied, the wafer stage starts the motion of scan and step. The left side of the figure 7 shows an instance in the motion. The water moves as it is dragged by the wafer motion. Some part of the water is outside the lens area, and there is some vacant space under the lens area. As shown this simulation, we can see how the water behaves, which helps us to consider effective methods of water supply and recovery.

Nikon has explored effective methods of local fill (supply and recovery) system. Figure 8 shows the result of one of successful cases. Water supply structure and recovery structure are assembled near the bottom lens position. The left side of the figure 8 shows an instance of water motion when the wafer stage is undergoing scan and step motion. We can see in the figure that the water is successfully confined in the limited region around the bottom of the lens. Also we can see within the center area, which is used for exposure, no vacancy of the water.

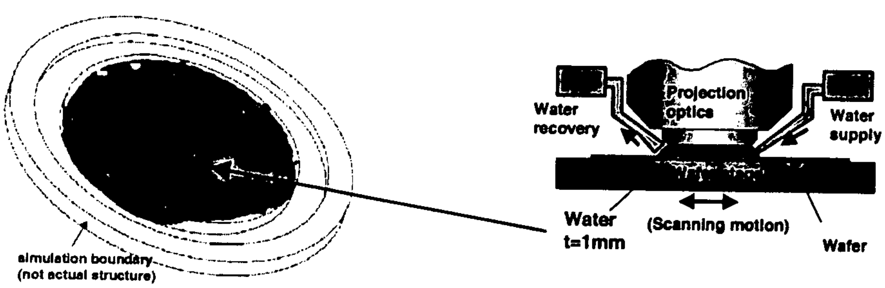

Figure 8 Fluid dynamic simulation results of local fill method with a water supply and recovery system.

For the next case we added the temperature distribution caused by the exposure heat. Figure 9 show the temperature distribution as well as water motion viewed from the wafer side.

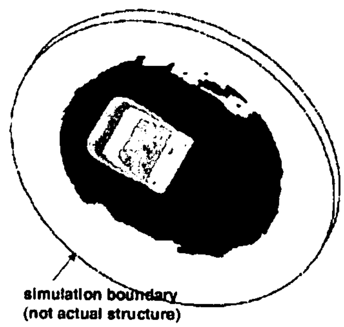

Figure 9 Fluid motion and temperature distribution during the scan and step motion and exposure (water-resist interface, viewed from wafer).

In the simulation shown in figure 9, the exposure light was assumed as continuous light with the same average power density of laser-pulse trains.

Based on these fluid dynamic and thermal simulations, we can understand the "local fill" method is basically feasible at least for exposures at the center area of the wafer. On the other hand, the exposure of the near the circumference of the wafer causes the "edge shot" issue. Nikon is planning to do experimental investigation of the "edge shot" issue in the next phase of feasibility study.

3.5 Bubble prevention and elimination

Bubbles present a new issue peculiar to immersion lithography. This issue needs attention because the bubbles are not only the sources of scattering of exposure light, but may also cause defects if the bubbles are attached on the surface of the wafer.

Nikon has investigated the bubble formation mechanism. We have understood that bubble formation occurs when the condition of liquid exceeds the capacity (saturation condition) of gas dissolution. In other words, liquid can contain some amount of gas in dissolved state, and generally the gas concentration is in the saturation condition, but when some parameter, such as temperature or pressure, changes beyond the saturation condition, bubbles are formed.

Looking into the past story for the bubble prevention and elimination in the industry, including wet-process in semiconductor fabs, we have found that the degassing is the most effective method to eliminate the bubbles. It is naturally understand by considering the mechanism of bubble formation. There are several methods of efficient degassing, some of which have been already realized as commercial products.

On the other hand, there is a concern about the degassed water lifetime. Even if we obtained perfectly degassed water, it will dissolve air through the boundary. We conducted an air dissolution simulation into the water that is filling the space between the bottom lens and the wafer. For the first trial, the water was assumed stationary. Figure 10 (left) shows the gas concentration status of the water at the timing of 456 seconds after the initial condition.

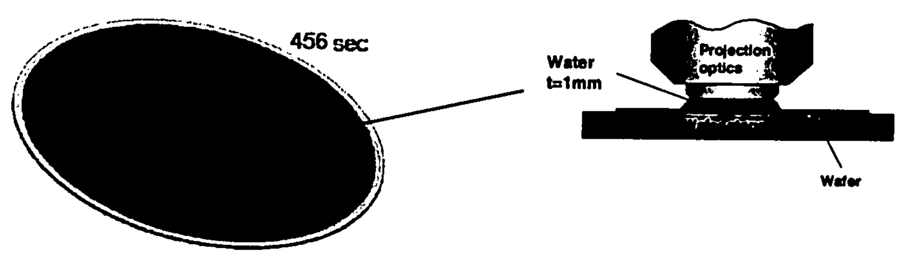

Figure 10 Air dissolution status to the degassed water at the timing of 456 seconds after the initial condition.

For the initial condition, fully degassed water is assumed filling in the space between the bottom lens and the wafer. Air dissolves into the water from the circumference boundary. Air concentration is depicted as the light tone of edge region in the left of figure 10. We can understand, even after the 456 seconds, the air dissolution is limited to the very boundary region of a few millimeters width. The center area that is used for exposure is still kept in its degassed state.

In this simulation, the water was treated as stationary. Therefore there is concern that the air dissolution may be faster if the water moves, due to random flow inside the water. On the other hand, the actual local fill method has a sufficient supply of fresh, degassed water. Therefore, air dissolution into the center area may be prevented by the fresh water supply. Nikon is doing a new simulation of air dissolution into the moving water with supply and recovery systems, and will obtain results soon.

Based on this simulation, we can conclude that if the degassing is the efficient method to bubbles, it is highly possible that bubble formation will be prevented in the local fill method.

3.6 Resist availability for water immersion

In 193nm immersion lithography, resist is exposed under water. The water may cause serious effects on the chemical reaction process inside the resist. To investigate this effect, we conducted immersion-imaging experiments in collaboration with Tokyo Ohka Kogyo (TOK). A standard two-beam interference method was adopted (figure 11).

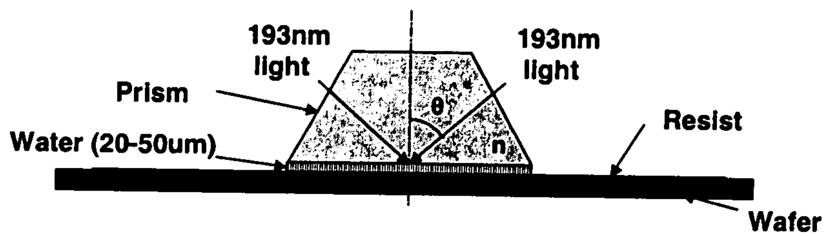

Figure 11 Schematic diagram of immersion exposure experiment

Between a prism made of fused silica and the resist, a thin layer of water (20-50μm) was established. A high-coherence, solid-state 193nm laser was used, which has exactly same wavelength, 193.37nm, as the ArF excimer laser. Repetition rate was 80kHz and average power was 10mW. Because of the high coherence of light, the set-up of the optics was not difficult. Resist was supplied by TOK.

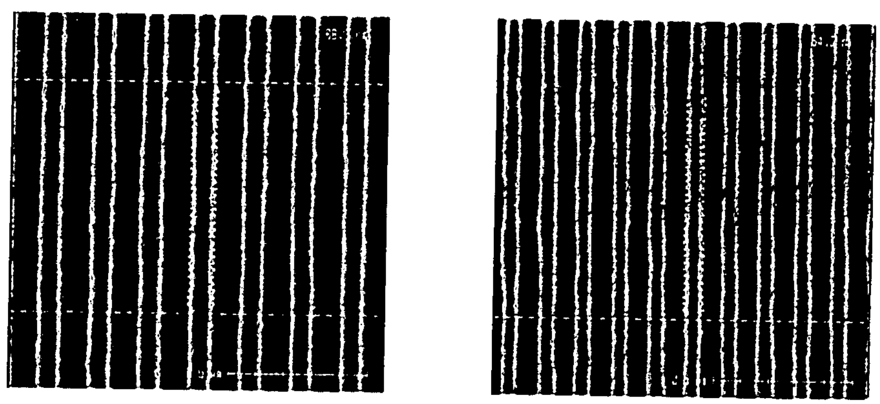

Figure 12 90 nm L/S (left) and 65 nm L/S (right) patterns by immersion lithography. 193nm light was generated with a high-coherence, solid-state laser. Immersion liquid was water.

Figure 12 shows the results (SEM image) of 90nm and 65nm L/S patterns. As shown in the figure 12, both 90nm L/S and 65nm L/S are successfully imaged. From these results, we can understand that there are some kinds of resists that are usable for water immersion lithography using 193nm exposure light.

3.7 Summary of fundamental issues

As was shown above, six issues are investigated. Nikon finds that all results are positive for feasibility, which means there are no "show stoppers" in those issues.

4. REMAINING ISSUES AND FEASIBILITY STUDY SCHEDULE

4.1 Remaining issues

Besides the fundamental issues, there are several issues more related to engineering. They are:

- Temperature control of liquid
- Liquid contamination
- Focus sensing
- Edge shot
- Throughput limitation study
- Experimental demonstration

We have a plan to investigate those issues in the next feasibility study, in which experiments will be made.

4.2 Feasibility study schedule

The first phase of the feasibility study in Nikon ended in March 2003, in which theoretical study, simulations and resist imaging experiments were conducted. Because the results are positive, the second phase of study was started with a plan to end in October 2003. Immersion lithography feasibility judgment of Nikon will be made in the fourth quarter of 2003.

5. CASE STUDY ON WAVELENGTH CHANGE

Here, we discuss briefly the strategy of wavelength change. We also consider the role of immersion lithography. Looking back at the history of exposure wavelength used in the lithography, and comparing it with the proposed roadmaps, we find a discrepancy between the history and the expectation.

We understand that, in these several years, we worked along with the strategy of "Change wavelength as soon as possible (ASAP)", which is depicted in figure 13:

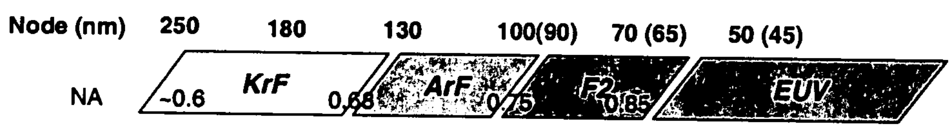

Figure 13 Old strategy of wavelength change: "Change wavelength as soon as possible (ASAP)"

In this strategy, ArF wavelength (193nm) was planned to start from 130-nm node, as well as F2 (157 nm) from 100-nm node, and EUV (13 nm) from 70-nm node. At present, however, most people know this strategy is a past story that could not be realized.

Instead, we might be better to seriously consider a new strategy: "Use one wavelength as long as possible (ALAP)" (Figure 14).

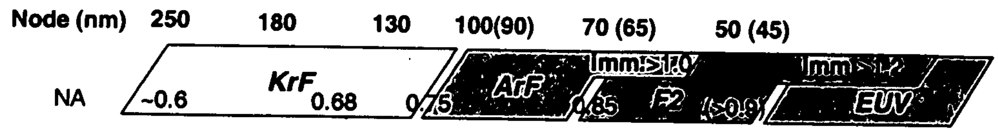

Figure 14 Proposed new strategy of wavelength change: "Use one wavelength as long as possible (ALAP)"

This strategy is based on the history of past 6 years. In these years, an "aggressive roadmap" of "two-year cycle" was successful. However, we should note that the success was made by using only one wavelength; KrF (248 nm), though intensive efforts of early ramp-up of ArF (193 nm) lithography have been made. We should be aware of the fact that wavelength change is a very slow process, compared with the process of changing NA or k_1.

The question is: "What about next 6 years?" Shall we change three wavelengths (ArF, F2, EUV) by the year 2009?

The answer is uncertain… Our message is that immersion lithography will extend the wavelength lifetime.

6. CONCLUSIONS

The potential advantage of immersion lithography was investigated. ArF immersion lithography using water can be understood as 134-nm lithography, which has equivalent or better performance compared to F2 dry lithography. Six fundamental issues have been studied. They are; full field projection optics, precise measurement of water parameter, thermal aberration in the water by exposure pulses, water supply mechanism, bubble prevention and resist availability for immersion lithography. All results of the study are positive for feasibility, at least there are no "show stoppers" among them. However, there are remaining engineering issues. Nikon is examining these issues in the next phase of feasibility study. Judgment timing inside Nikon is planned as the fourth quarter of 2003.

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